

# Optical flares from the faint mid-dM star 2MASS J00453912+4140395

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We present *B* and *V* light curves of a large stellar flare obtained with the Wide Field Camera at the Isaac Newton 2.5-m telescope (La Palma). The source object is a faint ( $m_V = 21.38$ ) foreground star in the field of the Andromeda galaxy, with its most probable spectral type being dM4. We provide an estimate of the total flare energy in the optical range and find it to be of the order of  $10^{35}$  erg. The cooling phase of the large flare shows three additional weak flare-like events, which we interpret as results of a triggering mechanism also observed on the Sun during large coronal mass ejections.

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## 1 Introduction

Flares are known as sudden and violent events releasing magnetic energy and hot plasma from the stellar atmospheres. We observe them on magnetically active stars and, much more closely, on the Sun. Electromagnetic radiation is emitted across the entire spectrum, from radio waves through the optical range to X-rays and  $\gamma$  rays. The total energy released during a typical solar flare is of the order of  $10^{30}$  erg, while the largest solar two-ribbon flares can emit up to  $10^{32}$  erg.

According to the accepted model of solar flares, in the upper atmosphere, between oppositely oriented magnetic field lines, a current sheet forms and magnetic reconnection takes place, which results in acceleration of particles, and thus produces electromagnetic radiation and plasma heating. On the basis of the solar paradigm one could simply expect that modelling stellar flares is just a question of scaling (e.g., as a function of the released energy, size, duration, etc.). However, besides general similarities, stellar flare observations also unveil problems that cannot be explained with the extended canonical solar flare model, arising from the different spectral distribution of the emitted energy, the role of age and spectral type of the host star, the multiform magnetic field topologies on stars, the tidal forces in active binaries, etc. The only way we can come closer to drawing up similarities and differences between solar and stellar flares is to continuously broaden the ensemble of analyzed flares (solar and stellar as well), thus making an observa-

tional base of different types of flaring activities available for theoretical purposes. This is how solar flare observations can help in the correct interpretation of stellar flares, and reversely.

Flare activity in cool stars is a very common phenomenon. Flares in stars with spectral types earlier than M are observed mainly in UV and X-rays and optical flares (like the most energetic white light flares in the Sun; Hudson, Wolfson, & Metcalf 2006) are rare. However, in the less luminous low-mass dM stars optical flares often occur. It is also known that red dwarfs from  $\approx 0.3M_{\odot}$  down to the hydrogen burning limit can release a considerable amount of energy via flare eruptions, even when, in most cases, these objects show very low magnetic activity in their quiescent state. In this paper we present photometric observations of a large optical flare event observed on 2000 September 25 that is associated with one such low-mass dM stars. In Sect. 2 a short description of the data is given, and in Sect. 3 we summarize the stellar properties of the host star. In Sect. 4 we give an estimate of the energy released by the large flare and, finally, in Sect. 5 an additional two weaker short-term flares are identified and a plausible scenario is set up for the three weak post-flare events that followed the large flare.

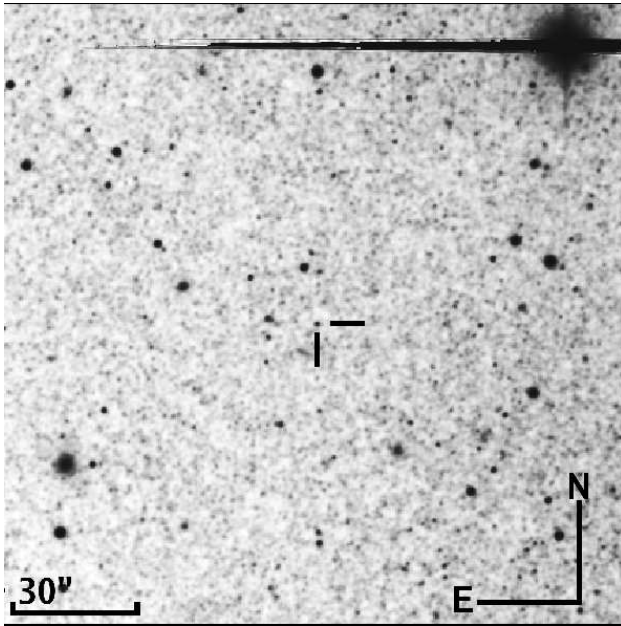
## 2 Data

Our time-series data were collected between 1999–2003 within the course of a variability survey in the North-Eastern quadrant of the Andromeda Galaxy (M31). The observations were acquired with the Wide Field Camera at the Isaac

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**Table 1** Catalog data on the observed target

	INT WFC	DIRECT	2MASS
object ID	M31_J00453912+4140395	D31J004539.1+414039.5	J00453911+4140396
$\alpha$ (J2000)	00 45 39.12	00 45 39.11	00 45 39.12
$\delta$ (J2000)	+41 40 39.5	+41 40 39.46	+41 40 39.7
$B$	23.18		
$\sigma_B$	0.11		
$V$	21.38	21.62	
$\sigma_V$	0.03	0.07	
$I$		18.18	
$\sigma_I$		0.07	
$J$			16.35
$\sigma_J$			0.11
$H$			15.98
$\sigma_H$			0.16
$K$			15.63
$\sigma_K$			0.18

**Fig. 1** Finding chart from the M31 field with our target (INT WFC image).

Newton 2.5-m telescope (INT) in La Palma (Spain). The program is described in detail in Vilardell, Ribas, & Jordi (2006). In brief, the observations, taken during the course of 21 nights, were reduced and then analyzed by means of the so-called Difference Image Analysis (DIA) technique, which is especially tailored to detect variable objects. The resulting data are high precision ( $\sim 0.01$  mag) photometric light curves in the Johnson  $B$  and  $V$  passbands. The object studied here, which has identifier M31\_J00453912+4140395 in the Vilardell et al. (2006) catalog, was flagged during the course of the analysis as an object with a large brightening following the characteristic light curve shape of a stellar flare. The finding chart of the object, also cross-identified as 2MASS J00453912+4140395, is shown in Fig. 1, which contains only a small portion of the full  $32' \times 32'$  field of

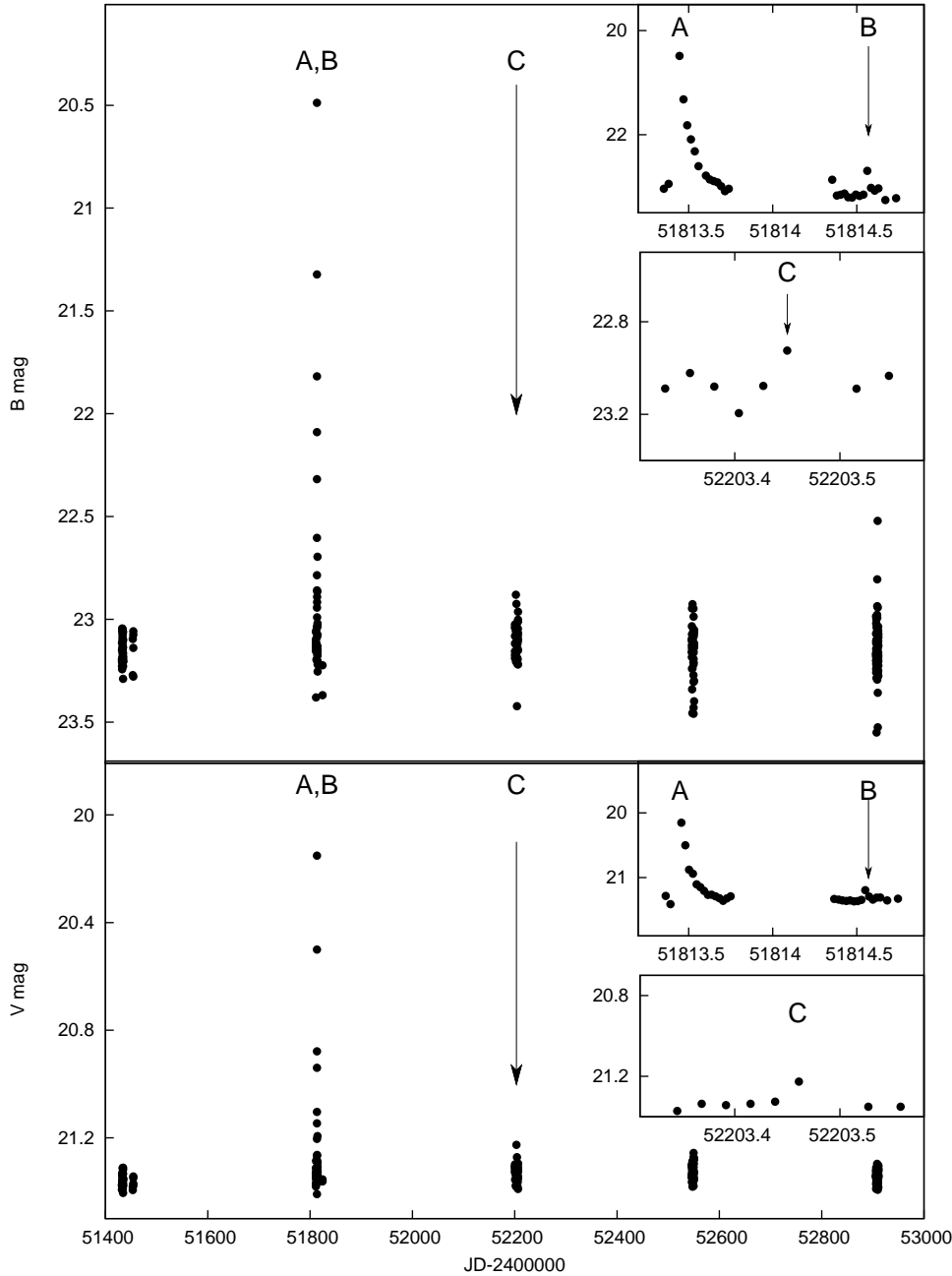
view of the WFC. The  $B$  and  $V$  observations resulting from the DIA analysis and subsequent calibration to the standard system are plotted in Fig. 2, where the large flare event (A) is zoomed alongside with two other weaker flares (B, C).

### 3 Stellar properties

Table 1 summarizes the quiescent  $B$  and  $V$  magnitudes from our INT data, as well as  $V$  and  $I$  magnitudes from the DIRECT catalogue (Mochejska et al. 2001), and  $J$ ,  $H$  and  $K$  magnitudes from the 2MASS catalogue (Skrutskie et al. 2006). A self-consistent analysis using the observed object color indices and the extinction law of Drimmel, Cabrera-Lavers, & López-Corredoira (2003) indicates a color excess of  $E(B - V) = 0.05$  mag, and, adopting a ratio of 3.1 between  $A_V$  and  $E(B - V)$ , leads to an absolute extinction of 0.16 mag. The unreddened color indices are most compatible with a spectral type M4 dwarf with  $M_V = 13.8$  mag,  $\log L/L_\odot \approx -2.5$ ,  $M \approx 0.16 M_\odot$ , and  $R \approx 0.2 R_\odot$  according to the tabulations from Baraffe & Chabrier (1996), Baraffe et al. (1998), and Bessell, Castelli, & Plez (1998). The distance resulting from the analysis is of roughly 300 pc.

KPNO plates taken from the M31 field (NOAO Science Archive, Aladin Sky Atlas, <http://aladin.u-strasbg.fr/>) also agree with a mid-M or later spectral type classification since the object is best seen in the  $I$ -band KPNO plates, but also observable in  $H\alpha$  and  $R$ . However, in the  $U$ ,  $B$ , and  $V$  band plates our target is indistinguishable from the background.

A first step towards evaluating the level of magnetic activity of the studied target is to investigate possible cyclic (rotational) variability induced by surface inhomogeneities (e.g., cool spots). No convincing sign of such modulation was found from our Fourier analysis. Three possible explanations can be put forward. First, spot coverage could be too small to observe any rotational modulation (this is the case when observing our Sun as a star in optical photometric bands). Alternatively, the star could be heavily spotted and yet show small or no modulation if spots are evenly dis-



**Fig. 2** Light curves in Johnson *B* and *V* bands of 2MASS J00453912+4140395 taken with the WFC of INT in La Palma, between 1999–2003. Three individual flare events (flares A, B and C) are marked and zoomed.

tributed. If we compare the mean error of the measurements in *B* is 0.08 mag with a scatter of 0.11 mag, i.e., there is still room for some low-level modulation, although the *V* band does not seem to show such behaviour with a scatter of 0.03 mag and a 0.04 mag formal error. The third possible scenario is a low inclination ( $i \approx 0^\circ$ ) of the rotation axis making it not possible to observe any rotational variability. However, in this latter case one could expect variability on a longer timescale of a few years, because of changes in the overall spot coverage according to solar-like spot activity cycle (see e.g. Oláh, Kolláth, & Strassmeier 2000). No

such long-term modulation is seen during the 5-year long observing season and 2MASS J00453912+4140395 seems to be like the vast majority of cool M dwarfs with rotational variability less than 1 – 2% in the visible.

#### 4 Flare energy estimation

Flare statistics of red dwarf stars show that stellar flares can generally be divided into two subgroups: a group consisting of relatively small, short ( $\approx 10^3$  s) impulsive flares, and a more energetic group releasing at least  $10^{32}$  erg and last-

ing  $\approx 10^4$  s. The latter are often related to solar two-ribbon flares which are associated to filament eruptions and coronal mass ejections (CMEs). The basic properties of flare A observed on 2000 September 25 (beginning at HJD 2451813.45), such as the long duration reaching  $\Delta t_B \approx 3 \times 10^4$  s and the large amplitudes of  $\Delta B = 2.69$  mag and  $\Delta V = 1.23$  mag clearly class this event among the more energetic group.

Flare light curves usually consist of a rapid rise followed by a slower, monotonic decay. However, our poorly covered rising phase permits only a rough estimate of the physical properties. For the estimation of the flare energy first we derived intensity from the magnitude values:

$$\frac{I_{0+f}}{I_0} = 10^{\frac{\Delta m_{B,V}}{2.5}}, \quad (1)$$

where  $I_{0+f}$  and  $I_0$  are the intensity values of the flaring and the quiescent stellar surfaces, respectively, in one of the observed bands. The relative flare energy is then obtained by integrating the flare intensity over the flare duration:

$$\mathcal{E}_f = \int_{t_1}^{t_2} \left( \frac{I_{0+f}(t)}{I_0} - 1 \right) dt. \quad (2)$$

The quiescent stellar fluxes in different bands are estimated assuming a simple black body energy distribution for a dM4 star with  $T_{\text{eff}} = 3100$  K and  $R \approx 0.2 R_{\odot}$  (see Sect. 3) from the equation

$$F_{\star} = \int_{\lambda_1}^{\lambda_2} 4\pi R^2 \mathcal{F}(\lambda) S_{B,V}(\lambda) d\lambda, \quad (3)$$

where  $\mathcal{F}(\lambda)$  is the power function and  $S_{B,V}(\lambda)$  is the transmission function for a given passband. Finally, the total integrated flare energy is calculated by multiplying the relative flare energy by the quiescent stellar flux:

$$E_f = \mathcal{E}_f F_{\star}. \quad (4)$$

Since our flare light curve is poorly covered, the abrupt rising phase with its real peak value may be estimated as even 1.5–2 mag brighter in  $B$  and  $\approx 1.3$  mag brighter in  $V$  than the measured maxima. This assumption corresponds to a photometric flare temperature of  $\approx 1.5 \times 10^4$  K at peak (cf., e.g., Ishida 1990; Ishida et al. 1991, and references therein). According to this, the observed and dereddened  $B - V$  peak of 0.29 mag is just an upper limit of a more reliable  $B - V \approx -0.16$  mag. Calculated luminosities for the quiescent star, and the total flare energy for both the minimum fit and the more realistic assumption are summarized in Table 2, together with the ratio of the flare energy and the quiescent stellar luminosity, often called equivalent flare duration, i.e., the time interval in which the star would radiate as much energy as the flare itself. The ratio between the flare energies  $E_B/E_V = 2.01$  (or 1.83 for the more realistic estimation) is of the order of the statistical value of  $1.60^{+0.13}_{-0.32}$  from Lacy, Moffett, & Evans (1976). Using the empirical correlation

$$E_U = 1.2 \pm 0.08 E_B \quad (5)$$

we obtain an estimation of  $4.27$  ( $7.61$ )  $10^{34}$  erg for  $E_U$ . From this we can estimate the total flare energy released in

**Table 2** Quiescent stellar flux and flare energy estimations. A minimum flare energy is estimated both from a minimum fit of the observed data and also by a (more realistic) reconstruction of the rising phase (values in parenthesis).

band	quiescent flux $10^{29}$ [erg/s]	flare energy $10^{34}$ [erg]	equivalent duration [h]
$B$	5.09	3.56 (6.34)	19.4 (34.6)
$V$	12.76	1.77 (3.47)	3.9 (7.6)

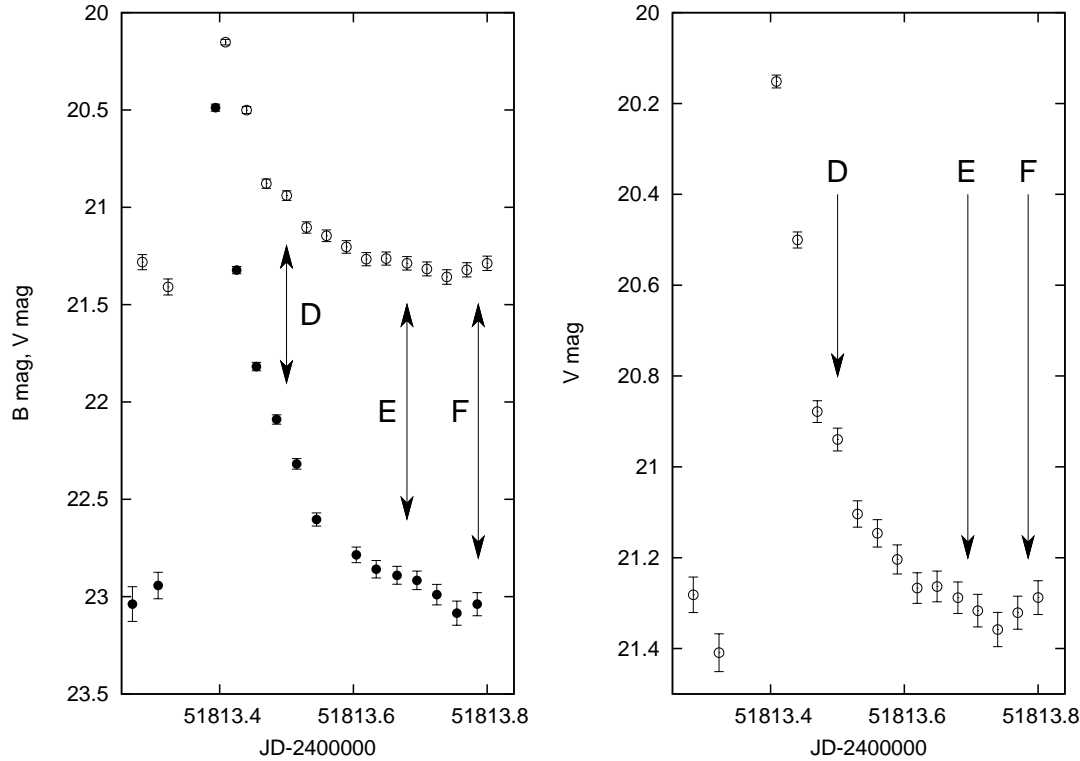
the optical range as being of the order of a few times  $10^{35}$  erg, and resulting in a value of  $\approx 10^{36}$  erg for the bolometric flare energy (cf. the review of Pettersen 1989). This rough but still realistic estimation (c.f. the example in Pagano et al. 1997 with  $\sim 3$  times more brightness in  $U$ ) indicates that the 2000 September 25 flare is among the most energetic stellar flares ever observed.

## 5 Weak flaring and post-flare events

There are statistical evidences that flare-like transient phenomena, often called microflares, are almost continuously present on M-type dwarfs. These events are thought to be one of the major sources of chromospheric and coronal heating. We see them (sometimes as nanoflares) also on the Sun (e.g., Lin et al. 1984), however, because of being relatively weak and short-term events most of them remain unresolved.

For filtering out such short-duration events from the background of our photometric data we searched for small amplitude peaks occurred simultaneously in both photometric colours. We applied different filtering algorithms but finally a visual inspection proved to be most reliable and efficient. Two such events are apparent. One is just one day after flare A at HJD 2451814.55 (marked with B in Fig. 2) and another one at HJD 2452203.45 (flare C in Fig. 2). There are some additional albeit less convincing ones, which are only  $2\text{-}\sigma$  away from the photometric background, and therefore were disregarded. Following the method described in Sect. 4, we estimate the total energy of flares B and C to be from a few times  $10^{32}$  erg up to  $10^{33}$  erg in  $B$ , which are characteristic of short-term impulsive flares rather than microflares.

When analyzing the decay phase of the light curve of flare A, three other short term increases can be identified. Since those events occurred simultaneously in both colours, we assume them to be an additional three weak flares: one at HJD 2451813.54 (D in Fig. 3), another one at HJD 2451813.67 (E) and a third one just at the end of the large flare light curve at HJD 2451813.74 (F), all of them lasting about  $\Delta t \approx 8 \times 10^3$  s (in the case of flare F, the simultaneous rise in  $B$  and  $V$  together is considered as just the beginning of the flare event and its duration is extrapolated). Again, we estimate the total flare energies as  $2 - 6 \times 10^{31}$  erg in  $B$  and about a half of this value in  $V$ . The occurrence of such weak post-flare events in the descending phase of a large long duration flare is a reminder of the mechanism described first by



**Fig. 3** The large flare of 2000 September 25 (flare A in Fig. 2) with three post-flare events (D,E and F). Left panel shows the  $B$  (dots) and  $V$  (circles) light curves together. In the right panel the zoomed  $V$  curve is plotted alone.

Attrill et al. 2007, which probably occurs on the Sun during large CMEs. After energetic solar flares are associated with CMEs, the moving footpoints of the blowing up magnetic loop crosstalk with opposite polarity flux ropes from the randomly distributed magnetic carpet, or other favourably oriented magnetic concentrations (active regions), thus forming current sheets and triggering other (micro)flare events from time to time. This seems a plausible interpretation for the three weak flare-like events (D, E and F) observed during the decay phase of flare A.

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## References

- Attrill, G.D.R., Harra, L.K., van Driel-Gesztelyi, L., Démoulin, P.: 2007, *ApJ*, 656, L101
- Baraffe, I., Chabrier, G.: 1996, *ApJ* 461, 51
- Baraffe, I., Chabrier, G., Allard, F., Hauschildt, P.: 1998, *A&A* 337, 403
- Bessell, M.S., Castelli, F., Plez, B.: 1998, *A&A* 333, 231
- Drimmel, R., Cabrera-Lavers, A., López-Corredoira, M.: 2003, *A&A* 409, 205
- Hudson, H.S., Wolfson, C.J., Metcalf, T.R.: 2006, *Sol. Phys.* 234, 79
- Ishida, K.: 1990, In: *Flare Stars in Star Clusters, Associations and the Solar Vicinity*, IAU Symp. 137, Mirzorian, L.V., Pettersen, B.R. and Tsvetkov, M.K. (eds), pp 43-47.
- Ishida, K., Mahasenaputra, Ichimura, K., Shimizu, Y.: 1991, *Ap&SS* 182, 227
- Lacy, C.H., Moffett, T.J., Evans, D.S.: 1976, *ApJS* 30, 85
- Lin, R.P., Schwartz, R.A., Kane, S.R., Pelling, R.M., Hurley, K.C.: 1984, *ApJ* 283, 421
- Mochejska B.J., Kaluzny J., Stanek K.Z., Sasselov D.D.: 2001, *AJ* 122, 1383
- Oláh, K., Kolláth, Z., Strassmeier, K. G.: 2000, *A&A* 356, 643
- Pagano, I., Ventura, R., Rodonò, M., Peres, G., Micela, G.: 1997, *A&A* 318, 467
- Pettersen, B.R.: 1989, *Sol. Phys.* 121, 299
- Skrutskie, M.F., Cutri, R.M., Stiening, R. et al., 2006, *AJ*, 131, 1163
- Vilardell, F., Ribas, I., Jordi, C., 2006, *A&A* 459, 321